Modelling climate change impact: A case of bambara groundnut (*Vigna subterranea*)

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ARTICLE INFO

ABSTRACT

Climate change projections for southern Africa indicate low and erratic rainfall as well as increasing frequency and intensity of rainfall extremes such as drought. The 2015/16 drought devastated large parts of southern Africa and highlighted the need for drought tolerant crops. Bambara groundnut is an African indigenous crop, commonly cultivated in southern Africa, with a higher potential for drought tolerance compared to other staple legumes. AquaCrop model was used to evaluate the impacts of climate change on yield, water use (*ET*) and water productivity (*WP*) of bambara groundnut using climate change data representative of the past (1961–1991), present (1995–2025), mid-century (2030–2060) and late century (2065–2095) obtained from five global circulation models (GCMs). The carbon dioxide (CO_2) file selected was for the A2 scenario. The model was run at a sub-catchment level. Model simulations showed that yield and *WP* of bambara groundnut will increase over time. The mean values of yield at the different time scales across the GCMs showed that yield of bambara groundnut increased by ~9% from the past to the present, will increase by ~15% from the present to mid-century and will increase by 6% from mid-to late-century. The simulated results of *ET* showed seasonal ranges of 703–796 mm. Of this, 45% was lost to soil evaporation, suggesting the need for developing bambara groundnut varieties with faster establishment and high canopy cover. Model simulations showed an increase in *WP* by ~13% from the past to present and ~15% from the present to mid-century and ~11% from mid-century to late century. While the results of these simulations are preliminary, they confirm the view that bambara groundnut is a potential future crop suitable for cultivation in marginal agricultural production areas. Future research should focus on crop improvement to improve current yield of bambara groundnut.

1. Introduction

South Africa is a water scarce country and receives less than 500 mm of rainfall annually (Mabhaudhi, 2012). Even then, much of this rainfall is unevenly distributed, falling mostly along the coastal areas. Resource poor households, the majority of whom rely exclusively on rainfed agriculture, often suffer significant yield losses (up to 50%) due to low and unevenly distributed rainfall (Chivenge et al., 2015). Climate change projections for South Africa suggest that the situation will only worsen in the near and late future. The recent Intergovernmental Panel on Climate Change (IPCC)'s fifth assessment report confirmed the climate change outlook for South Africa and much of sub-Saharan Africa (Pachauri et al., 2014). In addition to South Africa already suffering physical water scarcity, climate change impacts will be felt through low and erratic rainfall as well as increasing frequency and intensity of rainfall extremes, notably drought (Schulze, 2011). The

2015/16 drought, which is the worst to be experienced across southern Africa since records started being kept, has highlighted the sensitivity of smallholder agriculture to such extremes. While current approaches to climate change adaptation have yielded some positive responses, "there is a need for new and/or alternative approaches for ensuring food and nutrition security" (Chivenge et al., 2015) under increasing water scarcity. Consequently, there have now been suggestions to promote indigenous crop species as part of a key strategy to adapt to climate change (Mabhaudhi et al., 2016; Massawe et al., 2015).

Indigenous crop species are those that are native to a particular region, whose utilisation is currently confined to resource poor households, occupy low levels of utilisation, and are under-researched (Azam-Ali et al., 2001). These crops have been touted as possessing tolerance to several abiotic stresses (Mabhaudhi et al., 2016) as well as high nutritional yield (Mabhaudhi et al., 2016) and are being promoted as possible future crops. An example is bambara groundnut (*Vigna*
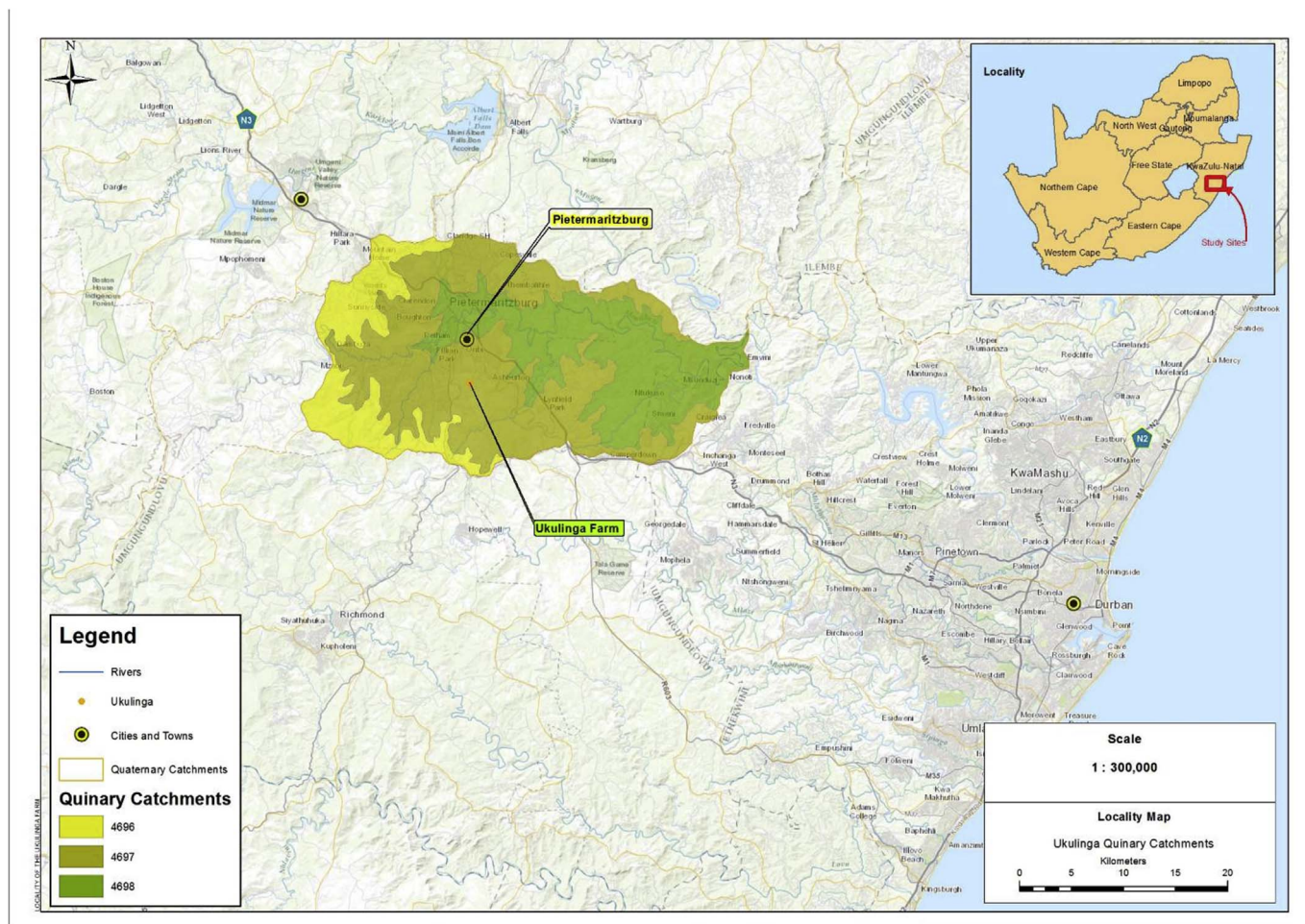
Fig. 1. Location of Ukulinga Research Farm in relation to the quinary sub–catchment.

subterranea L. Verdc), which is indigenous to Africa. Bambara groundnut is an indigenous African legume that is cultivated across sub–Saharan Africa (Mabhaudhi and Modi, 2013). It is an excellent source of proteins (19–22%) (Akande, 2009) calcium (2.19%) (Yao et al., 2015) and zinc (0.79%) (Yao et al., 2015). It also contains comparatively high levels of amino acids like methionine, leucine, tyrosine and arginine (Akande, 2009). Bambara groundnut is often consumed as a compliment to cereal based diets (Minka and Bruneteau, 2000). This makes it of nutritional importance in rural areas where people often suffer from malnutrition. However, although it was once popular, it has been displaced in cropping systems by the promotion of the exotic groundnut (*Arachis hypogea*) (Mabhaudhi and Modi, 2013).

Bambara groundnut is most impressive in terms of drought tolerance. Briefly, drought tolerance in plants is achieved through three separate mechanisms, namely, avoidance, escape and tolerance (Turner et al., 2001; Araus et al., 2002; Farooq et al., 2009). Most crops that are reported to be drought tolerant will often possess at least one or two of these mechanisms. Studies have confirmed drought avoidance and escape (Collinson et al., 1997; Jørgensen et al., 2010; Mabhaudhi and Modi, 2013) as well as low water use (Chibarabada et al., 2015; Mabhaudhi et al., 2013) as key characteristics allowing bambara groundnut to survive in harsh environments. More recently, Chai et al. (2016) observed drought tolerance in bambara groundnut. Thus, bambara groundnut possesses all three mechanisms of drought tolerance; this makes it a model crop capable of producing reasonable yields under mild, intermittent and severe drought stress. As a drought tolerant crop and with good nutritional yield, there is a need to explore bambara groundnut production in dry areas of South Africa, especially

under climate change scenarios.

While there are reports of bambara groundnut drought tolerance and adaptation to semi-arid environments, there is a gap in knowledge concerning climate change impacts on bambara groundnut. This information is critical for the continued promotion of bambara groundnut as an alternative crop for climate change adaptation in dry areas of South Africa and the region. It was hypothesised that climate change had no impact on bambara groundnut yield, water use and water productivity. Thus, the aim of the current study was to determine the impacts of climate change, at sub-catchment scale, on yield, water use and water productivity of bambara groundnut for South Africa.

2. Materials and methods

Model simulations were done using the Food and Agriculture Organisation's (FAO) AquaCrop crop model (Version 4.0) (Raes et al., 2009; Steduto et al., 2009). The model was selected because it is a simple and robust water–driven model capable of simulating yield response to water (Mabhaudhi et al., 2014a); it is effective in regions where water is a limiting factor (Raes et al., 2009). In addition, AquaCrop is equipped with a variable water productivity (*WP*) parameter that considers crop response to carbon dioxide (CO_2) and has been tested against Free Air Carbon Enrichment (FACE) experiments thus making it ideal for assessing climate change impacts. Furthermore, AquaCrop has previously been successfully parameterised and validated for bambara groundnut (Mabhaudhi et al., 2014a).

2.1. Study area

The study site was the University of KwaZulu-Natal's Ukulinga Research Farm (29°40′S; 30°24′E; 809 m above sea level). Ukulinga represents a semi–arid climate with mean annual precipitation of 750 mm spread over 113 rain days of which 23% is received during the winter months. The estimated mean annual temperature is 18.3 °C with February (26.5 °C) and July (8.0 °C), respectively, the hottest and coldest months (Kunz et al., 2016). The soils are characterised as clay–loam soils and are moderately shallow ranging from 0.6 m to 1 m. Ukulinga is located within quaternary catchment U30D and quinary sub–catchment 4718 (Fig. 1). Briefly, a quaternary is a fourth level division of a primary catchment. Each quaternary catchment is then further sub–divided into three quinary sub–catchments based on altitude. For detailed explanations, the reader is referred to Schulze et al. (2011).

2.2. Brief description of AquaCrop

The FAO's AquaCrop model is a water–driven, canopy level and engineering type of crop model because it is functional and based on a mixture of well-established theories and empirical relationships (Steduto et al., 2009). AquaCrop simulates yield response to water under wide ranging conditions and for various crops (Raes et al., 2009; Steduto et al., 2009). The model represents an evolution in the understanding of soil–water–plant relations and yield response to water that emanated from FAO Paper No. 33 (Doorenbos and Kassam, 1979) to the most recent FAO Paper No. 66 (Steduto et al., 2012). AquaCrop's main distinguishing features from previous approaches include (i) the ability to use a simple canopy growth and senescence equation to (ii) separate evapotranspiration (ET) into soil evaporation (E_s) and crop transpiration (T_r), (iii) calculate yield (Y) as a function of biomass (B) and harvest index (HI), and (iv) to segregate the effects of water stress into four components – canopy growth, canopy senescence, stomatal closure and HI.

Another evolution relates to AquaCrop's use of cumulative transpiration (T_r) and a normalised water productivity (WP) parameter to calculate biomass (B):

$$B = WP \times \sum T_r$$

Water productivity is normalised by dividing the daily T_r by the daily ET_o. The normalisation of WP makes it more conservative and applicable to diverse locations and climates (Steduto et al., 2007). The equation runs on a daily time step (Raes et al., 2009; Steduto et al., 2009), which brings it closer to the time scale of crop responses to water stress (Acevedo et al., 1971). The model can also run using monthly or mean decade temperature, rainfall and ET_o records which it approximates into daily time steps when running (Raes et al., 2009). This adds to the model's simplicity which is coupled to the model's fewer input requirements relative to other crop models (Farahani et al., 2009; Steduto et al., 2009; Vanuytrecht et al., 2014). This is designed to make the model applicable in areas with limited data sets.

2.3. Simulations

The AquaCrop model (v4.0) was used to simulate yield responses to water for bambara groundnut under climate change scenarios, using the A2 scenario for sub-catchment 4718 in South Africa (Schulze et al., 2011). Similar to other crop models, AquaCrop requires user defined input files for climate (*.CLI), soil (*.SOL) and crop (*.CRO) to run. AquaCrop has already been parameterised and validated for a South African bambara groundnut landrace (Mabhaudhi et al., 2014a). Therefore, only climate and soil file descriptions are provided below.

2.3.1. Climate files

The climate file requires input files of maximum and minimum air temperature (*.TMP), rainfall (*.PLU) and reference evapotranspiration (*.ET_o). In order to develop climate files for AquaCrop, the quinary database for South Africa was used. Briefly, South Africa has been delineated into 5838 quinaries or sub–catchments (Schulze et al., 2011). The quinary climate database contains 50 years (1950–1999) of daily observed rainfall and temperature data deemed representative of each of the 5838 sub–catchments (Schulze et al., 2011). The daily temperature data were used to estimate relative humidity. Solar radiation for each sub-catchment was then calculated using the technique described by Schulze et al. (2007). From this, daily estimates of Penman-Monteith reference evapotranspiration (Allen et al., 1998) were derived assuming a default wind speed of 1.6 m s^{-1} (Schulze et al., 2007).

In addition to historical data, the quinary database also contains downscaled future climate projections for each quinary. The climate projections were developed by the University of Cape Town's Climate Systems Analysis Group (CSAG) and the Council for Scientific and Industrial Research (CSIR) using output from global climate models (GCMs). The GCMs provide daily rainfall and temperature scenarios for a continuous period from 1961 to 2100. Owing to the disparity in spatial resolution between coarse–scale GCM output and the fine–scale input needs of impact models, there is a need to downscale GCMs outputs. There are two fundamental approaches for downscaling large-scale GCM output to a finer spatial resolution. The first of these is a dynamic approach described by Engelbrecht et al. (2011) where a higher resolution climate model is embedded within a GCM to produce a regional climate model (RCM). The second approach involves the use of statistical methods to establish empirical relationships between GCM–resolution climate variables and the local climate (Hewittson and Crane, 2006). Both methods were used to develop downscaled daily rainfall and temperature data for the quinary database. Daily reference crop evaporation estimates were then computed as described for the historical data set. The quinary climate database, therefore, satisfies AquaCrop's climate file input requirements.

For the current study, the quinary database was used to develop climate files for AquaCrop representative of the past (1961–1991), present (1995–2025), mid-century (2030–2060) and late century (2065–2095) obtained from an ensemble of five GCMs (Table 1).

2.3.2. Soil file

AquaCrop's soil file (*.SOL) requires input parameters for soil texture, permanent wilting point (PWP), field capacity (FC), saturation (SAT) and saturated hydraulic conductivity (K_{sat}). The university's Ukulinga Research Farm is located within sub-catchment 4718. Therefore, soil characteristics for Ukulinga (Mabhaudhi et al., 2014b) were used to develop the soil file (*.SOL) in AquaCrop (Table 2).

2.4. Statistical analyses

Following input files development, the AquaCrop model was then run for the corresponding periods – past (1961–1991), present (1995–2025), mid-century (2030–2060) and late century (2065–2095). Model outputs for B, Y, ET and WP [yield (kg) per water evapotranspired (m^3)] were then subjected to statistical analyses. Descriptive statistics such as means, standard deviations, and box and whisker plots were used to evaluate climate change impacts on B, Y, ET and WP for bambara groundnut. Box and whisker plots, coupled with standard deviations, can show stability and general distribution of data sets. The past (1961–1991) was used to describe the baseline for purposes of comparing climate change impacts. The performance of individual GCMs was also evaluated using a similar statistical approach.

Table 1
Summary of General circulation models (GCMs) used in the study (Source: Randall et al., 2007).

Model	Abbr.	Sponsors and country	Atmosphere resolution	Ocean resolution
CSIRO-Mk3.5	CSI	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research Australia	top = 4.5 hPa ($\sim$1.9° × 1.9°) L18	0.8° × 1.9° L31 depth
GFDL-CM2.0	GF0	U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)/ Geophysical Fluid Dynamics Laboratory (GFDL), USA	top = 3 hPa 2.0° × 2.5° L24	0.3°–1.0° × 1.0° depth
MIROC3.2-MEDRES	MIR	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	top = 30 km ($\sim$2.8° × 2.8°) L20	0.5°–1.4° × 1.4° L43 sigma/depth
MPI-ECHAM5	MPI	Max Planck Institute for Meteorology, Germany	top = 10 hPa T63 ($\sim$1.9° × 1.9°) L31	1.5° × 1.5° L40 depth
UKMO-HADCM3	UKM	Hadley Center for Climate Prediction and Research/Met Office UK	top = 5 hPa 2.5° × 3.75° L19	1.25° × 1.25° L20 depth

Notes: Top = atmospheric pressure at the top of the model, Horizontal resolution = degrees latitude by longitude. Vertical resolution (L) is the number of vertical levels into the atmosphere or ocean.

Table 2
Soil parameters used to develop the soil file for AquaCrop. Source: Mabhaudhi et al. (2014).

Textural class	^{v}PWP vol %	^{w}FC (mm m^{-1})	^{x}SAT (mm day^{-1})	^{y}TAW	^{z}Ksat
Clay	28.3	40.6	48.1	123	25.0

vPWP – permanent wilting point; wFC – field capacity; xSAT – saturation; yTAW – total available water; zKsat – saturated hydraulic conductivity.

3. Results and discussion

3.1. Rainfall data

Overall, all GCMs showed that the mean annual precipitation across the time periods was somewhat constant (1048 mm ± 183 mm) relative to the baseline (1165 mm); however, variations were observed across the simulated periods (Fig. 2). Across all GCMs, the trend was such that there was a reduction in rainfall across timescales [past (1151 mm) > present (1098 mm) > mid-century (1010 mm) > late century (931 mm)]. This implies a future reduction in rainfall for the site relative to the baseline. As such, water availability for crop production will be negatively affected. This implies that there is a need to identify crops with low levels of water use that could be introduced into the environment.

Among the GCMs, magnitude of rainfall reduction across timescales was observed to vary (Fig. 2). The highest reduction (25%) in rainfall between the past and late century timescales was observed under MIR model, while the least (14%) reduction was under the CSI model. Models GFO, MPI and UKM were somewhat consistent and showed average reductions of 17, 18 and 19%, respectively, between the past and late century periods. The observed results could be attributed to

differences in model resolution. Inter-seasonal rainfall variations were different across the different timescales and for each model. Overall, high rainfall variation was observed for MIR (1020 ± 182 mm) while the least variation was observed for CSI (1035 ± 140 mm) and GFO (1034 ± 134 mm). In the absence of observed values for intra-season variation for the simulated periods, the GCM simulated inter-seasonal variation could be considered acceptable as it is within the range of variation of baseline observations. In southern Africa, water is already limiting in agriculture and increased rainfall variability will worsen the situation (Schulze, 2011).

3.2. Yield and biomass

For the GCMs used and across the timescales, the observed trend was such that there was an increase in simulated biomass (B) and yield (Y) for bambara groundnut across timescales relative to the baseline (Figs. 3 and 4). The observed trend for simulated B and Y was such that past (7.6 and 1.6 t ha^{-1}) < present (8.6 and 1.8 t ha^{-1}) < mid-century (9.8 and 2.0 t ha^{-1}) < late century (10.8 and 2.2 t ha^{-1}). This showed a 42.5 and 37.5% increase in B and Y, respectively, between the baseline (past) and late century periods. Among the GCMs, the magnitude of change across the timescales for simulated B and Y was inconsistent. The observed variation was inconsistent with projected rainfall and expected increases in CO_2 emissions. It could be that other environmental factors such as temperature could have an impact on simulated biomass and yield results. Large variations within each timescale for different GCMs were also observed for B. Overall, B was more stable with an average of 9.2 ± 1.3 t ha^{-1} with a range of 4.8 t ha^{-1}. On the other hand, bambara groundnut yield was relatively less stable within each timescale for the different GCMs. Overall, yield was 1.9 ± 0.3 t ha^{-1} and an average range of 1.2 t ha^{-1}. This relates to
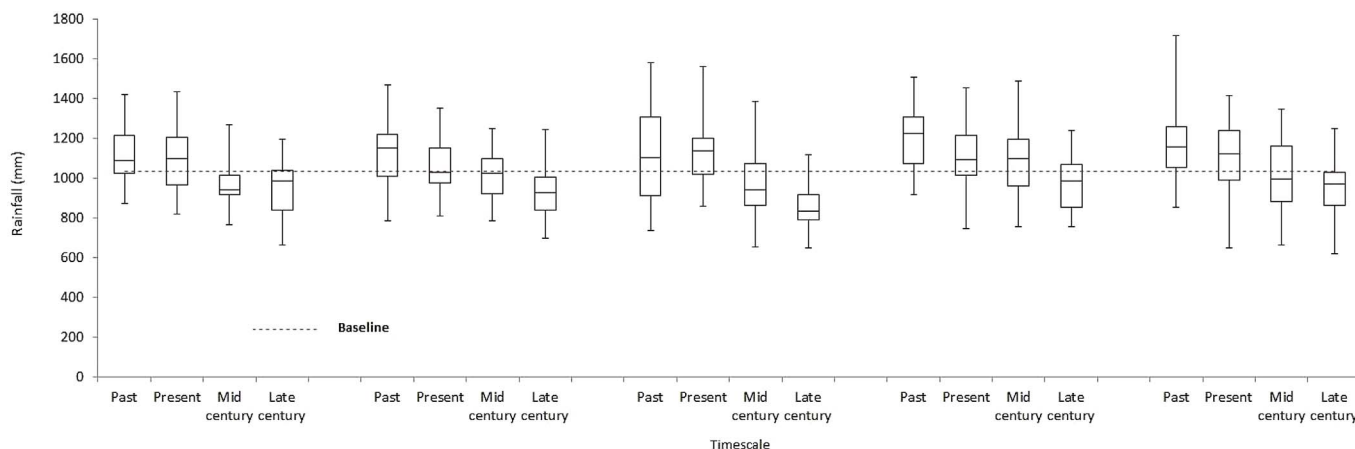

Fig. 2. Rainfall data representative of four different timescales (past, present, mid-century and late century) as simulated by five global circulation models (CSI, GFO, MIR, MPI, UKM).
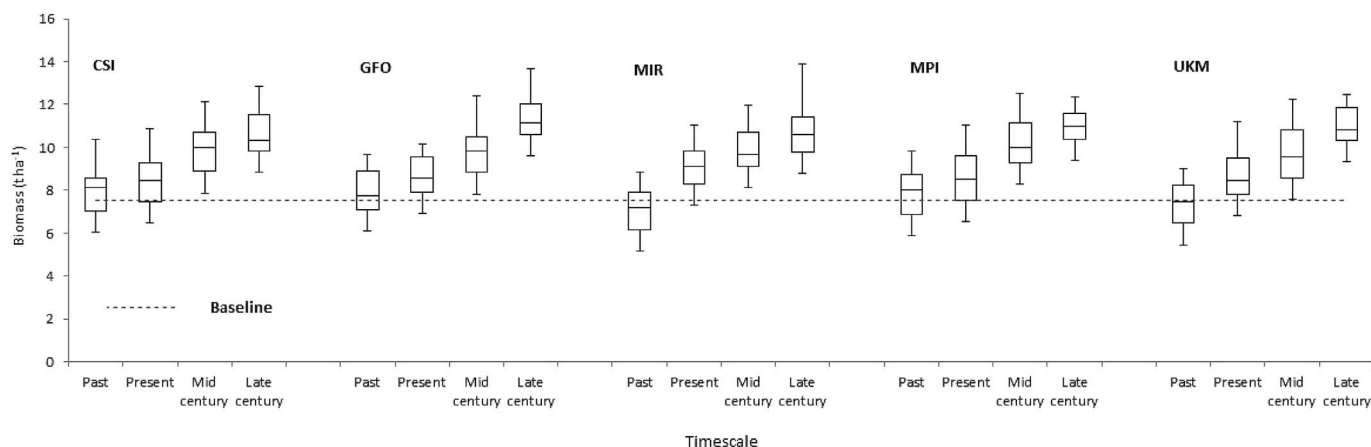
Fig. 3. Simulated biomass (t ha^{-1}) of bambara groundnut during four different time scales (past, present, mid-century and late century) under rainfed conditions obtained from five different global circulation models (CSI, GFO, MIR, MPI, UKM).
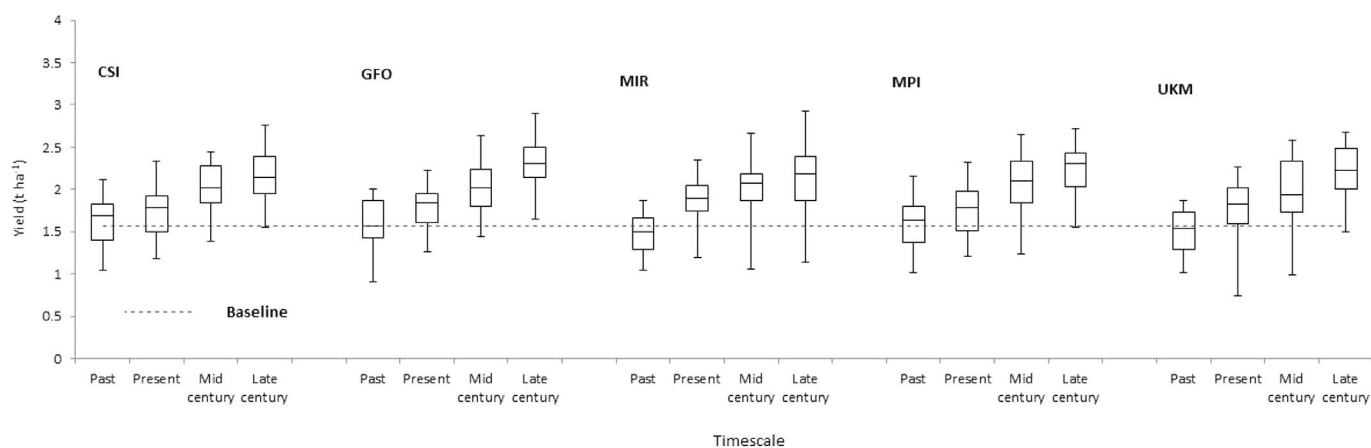

Fig. 4. Simulated yield (t ha^{-1}) of bambara groundnut during four different time scales (past, present, mid-century and late century) under rainfed conditions obtained from five different global circulation models (CSI, GFO, MIR, MPI, UKM).
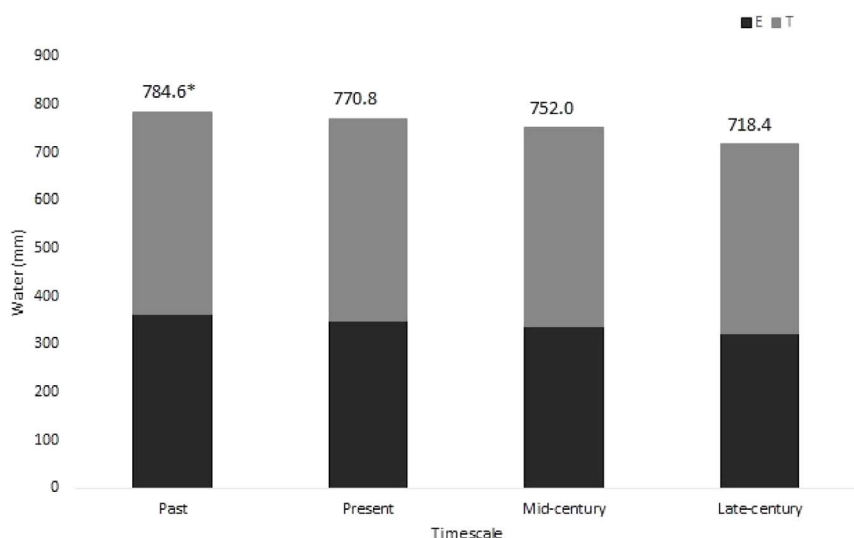

Fig. 5. Mean soil evaporation (E_s), transpiration (T_r) and evapotranspiration (ET)* of soybean and bambara groundnuts as simulated by five global circulation models (CSI, GFO, MIR, MPI and UKM) during four time scales (past, present, mid-century and late-century).

the sensitivity of *HI* responses to stresses (Mabhaudhi and Modi, 2013; Mabhaudhi et al., 2014a). The need for high and stable *HI* has previously been suggested as a target for future crop improvement (Mabhaudhi and Modi, 2013).

The observed increase in simulated *B* and *Y* of bambara groundnut (Figs. 3 and 4) for the present, mid-century and late-century periods relative to the baseline can be attributed to an increase in CO_2 and related to the photosynthetic pathway of bambara groundnut. Projected increases of CO_2 concentration will increase photosynthesis of C3 crop species by 30–50%. The primary enzyme in leaf photosynthesis of C3 plants, ribulose 1, 5- bisphosphate carboxylase/oxygenase (Rubisco), can bind to either CO_2 or O_2. Under elevated concentrations, CO_2
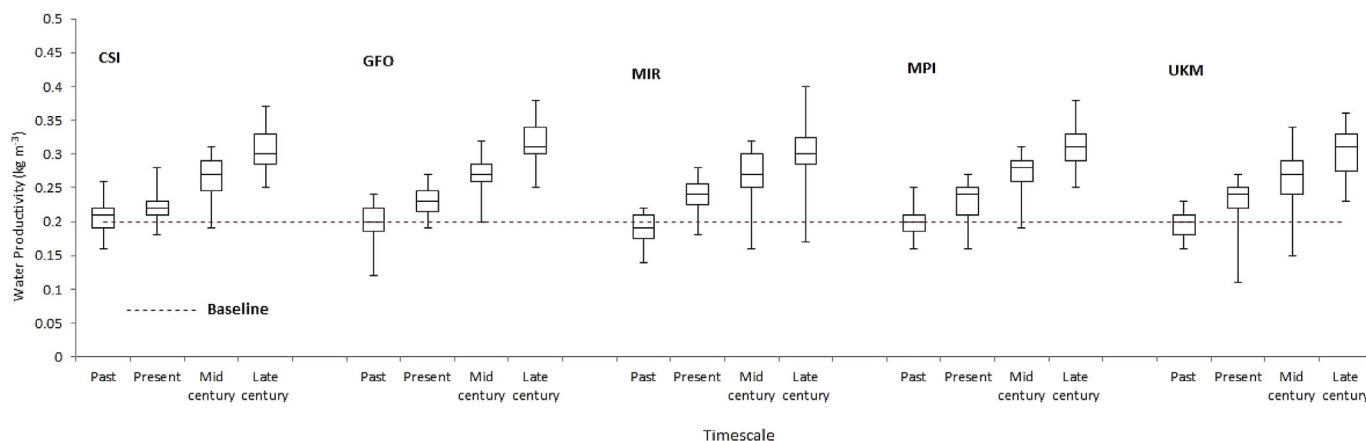
Fig. 6. Simulated *WP* (kg m^{-3}) of bambara groundnut during four different time scales (past, present, mid-century and late century) under rainfed conditions obtained from five different global circulation models (CSI, GFO, MIR, MPI, UKM).

competes more efficiently with dissolved O_2 for binding sites on Rubisco, thus leading to an increase of photosynthesis in C3 species. (Cure and Acock, 1986; Kimball and Idso, 1983; Sakurai et al., 2011). Chung et al. (2011) and Lal et al. (1998) also simulated an increase in rice yields due to increases in CO_2.

3.3. Water use

Water use trends showed that regardless of GCM, soil evaporation (E_s) and crop transpiration (T_r) decreased across timescales (Fig. 5). This contributed to the reduction in total evapotranspiration (*ET*) over the simulated periods [past (784 mm) > present (771 mm) > mid-century (752 mm) > late century (718 mm)]. This was consistent with projected decreases in rainfall across the simulated time periods. The reduction in T_r was observed to be on average 5.8% across GCMs and timescales. While the reduction in T_r was consistent with the reduction in rainfall, the magnitude of reduction suggests that rainfall received during the late century, coupled with an increase in CO_2 concentration, could still meet crop water requirements for bambara groundnut. This strengthens reports that bambara groundnut was adapted to future climate.

AquaCrop's ability to separate *ET* into and E_s and T_r is one of the model's distinguishing features and allows for an objective assessment of productive *vs.* non-productive water losses. It was observed that E_s under bambara groundnut production was projected to decline by 11.5%. This could be attributed to a reduction in soil wetting intervals due to reduced rainfall. It was also observed that, on average for all simulated periods, E_s constituted ~45% of total *ET*. This confirmed reports that a significant amount of water was lost to E_s in bambara groundnut production due to slow canopy establishment (Mabhaudhi and Modi, 2013; Mabhaudhi et al., 2014a). Thus, crop improvement should focus on developing bambara groundnut varieties that are quick to establish and with high canopy cover (Mabhaudhi and Modi, 2013). As an adaptation strategy, bambara groundnut could be intercropped with other crops that have high canopy cover to ensure maximum ground cover and reduction in E_s (Mabhaudhi et al., 2014a).

3.4. Water productivity

Simulated results for crop water productivity (*WP*) showed that it was projected to increase across timescales (Fig. 6). The trend was such that past (0.20 kg m^{-3}) > present (0.23 kg m^{-3}) > mid-century (0.27 kg m^{-3}) > late century (0.30 kg m^{-3}). Overall, *WP* is expected to increase by an average of 33% by the late century relative to the baseline. These results are consistent with observed increases in *B* and *Y*, and reduction in *ET*. Thus, improvements in *WP* were attributed to bambara groundnut's ability to maintain and/or improve *B* under

conditions of decreasing water availability. In addition, bambara groundnut's *HI* has been reported to be positively impacted by water stress hence the improvements in *Y* under decreasing *ET* (Mabhaudhi et al., 2014a). In addition, as a C3 crop, bambara groundnut productivity responded positively to increases in atmospheric CO_2 hence the increases in *B*, *Y* and *WP* (Cure and Acock, 1986; Kimball and Idso, 1983; Sakurai et al., 2011).

4. Conclusion

Based on simulations conducted for the current study, *Y* of bambara groundnut will increase by ~37.5% in response to projected climate change. Projected climate change is also expected to result in a 33% increase in *WP* for bambara groundnut. The increase in *WP* is linked to improvements in *B* and *Y* relative to decreasing *ET* due to decreasing rainfall i.e. 'more crop per drop'. Improving *WP* in rainfed cropping systems is a priority for climate change adaptation under increasing water scarcity. Thus, bambara groundnut should be promoted as a potential future crop for climate change adaptation in areas projected to receive low and variable rainfall coupled with increased frequency and intensity of weather extremes such as drought. The fact that a significant amount of water continues to be lost through E_s highlights the need for rainwater harvesting and conservation practices in rainfed cropping systems. There is also a need for crop improvement to develop new bambara groundnut varieties with uniform establishment and high canopy cover to minimise E_s losses and maximise T_r. While the results of these simulations are preliminary, they confirm the views that bambara groundnut is a drought tolerant crop suitable for cultivation in marginal agricultural production areas.

Conflicts of interest

The authors declare no conflict of interest.

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